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Technology Development for a Potential Hybrid Mars Ascent Vehicle

Ashley C. Karp*[a], Barry Nakazono [b], George Story[c], Jessica Chaffin[d], and Britt Oglesby[e]

[a] *Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109*, ashley.c.karp@jpl.nasa.gov
[b] *Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109*, barry.nakazono@jpl.nasa.gov
[c] *NASA Marshall Space Flight Center, Huntsville, AL 35812*, george.story@nasa.gov
[d] *NASA Marshall Space Flight Center, Huntsville, AL 35812*, jessica.chaffin@nasa.gov
[e] *NASA Marshall Space Flight Center, Huntsville, AL 35812*, britt.a.oglesby@nasa.gov

* Corresponding Author

Abstract

With Mars Sample Return mission concepts being considered for launch as early as 2026, technology development to enable this potential campaign is currently underway. One of the critical items in the campaign would be a Mars Ascent Vehicle, which would be responsible for getting the samples from the surface of Mars to orbit around Mars. This would be the first rocket launch from another planet. Therefore, several challenges arise due to the Martian atmosphere and remote location. A technology development program to determine the feasibility of a hybrid rocket for a Mars Ascent Vehicle is entering its fourth year. Highlights and successes of this program will be discussed.
Keywords: Mars, Ascent, Hybrid, Rocket, Sample Return

Acronyms/Abbreviations

Several acronyms will be used throughout this work. These include the following: Coefficient of Thermal Expansion (CTE), Liquid Injection Thrust Vector Control (LITVC), Mars Ascent Vehicle (MAV), Mars Sample Return (MSR), Mixed Oxides of Nitrogen (MON), Sample Return Lander (SRL), Single Stage to Orbit (SSTO), Technology Readiness Level (TRL), Thrust Vector Control (TVC), Triethyl Aluminium (TEA) and Triethyl Boron (TEB).

1. Introduction

A hybrid propulsion system is currently being investigated for a potential Mars Ascent Vehicle (MAV) because of its predicted low temperature compatibility (colder than -70 C), ability to restart and high performance (greater than 305 s Isp). While hybrid rockets, which typically utilize a solid fuel and liquid oxidizer, have been known for many years, they have not been developed to the same level of maturity as other propulsion options. This is mainly due to the low regression rate of conventional hybrid fuels, which translates into impractically low thrust for applications as large as a Mars Ascent Vehicle. However, the discovery of liquefying fuels approximately 20 years ago has brought renewed interest to this propulsion system. The Mars ambient conditions (low and variable temperatures) have brought focus to hybrid rockets as a potential solution because they are predicted to survive at lower temperatures than alternative solutions. Therefore, the hybrid option could offer substantial system power and mass savings.

Several years of development have been completed with the goal of raising the Technology Readiness Level (TRL) of the hybrid MAV concept. A wax-based fuel called SP7 was developed specifically for this application[1]. The storable oxidizer is Mixed Oxides of Nitrogen (MON), which is nitrogen tetroxide (N_2O_4) mixed with NO. Both MON-3 and MON-30 will be discussed here, which are N_2O_4 with 3% NO and 30% NO by mass, respectively. Testing of the SP7 with MON-3 has been completed at the small (7.5 cm) and near full (28 cm) scale at two subcontractors: Space Propulsion Group and Whittinghill Aerospace. The hybrid concept from the December 2016 Point of Departure Review (PoDR)[2] has been used to represent full scale. Requirements for this potential mission have not yet been determined, therefore the design will likely continue to evolve. The Sample Return Lander (SRL), which would house the MAV, will drive its mass and geometric constraints. These constraints are currently bounded by a 400 kg lift off mass, 3 m length and 0.57 m diameter. The payload and interface have an allocation of 18 kg for the purpose of this development program.

Liquid Injection Thrust Vector Control (LITVC) has been demonstrated by injecting MON-3 into the nozzle of the 28 cm motor. This method of thrust vector control

(TVC) was initially selected for its low temperature compatibility and will employ MON-30 in the flight configuration. More conventional TVC systems require soft goods or lubricants (e.g. standard flex seal and trapped ball designs). Since the MON-30 is already carried onboard, only a small amount of additional plumbing is required. Valve operation at low temperature is fairly well understood since gas blowdown systems often reach the temperatures of interest.

Finally, hypergolic ignition of SP7 mixed with Sodium Amide ($NaNH_2$) has been demonstrated at Purdue. Multiple ignitions of a SP7 grain with a relatively high loading of $NaNH_2$ have been successful and have led to the desire to investigate more reactive additives in order to minimize the ignition delay and the additive loading.

The major concern with this new propellant combination is ensuring it works well after being thermal cycled on the journey to and in the Mars environment. This will require careful design, with special attention paid to the thermal expansion and contraction. A preliminary investigation into this challenge will be presented.

2. Mars Sample Return and the Benefits of a Hybrid Rocket for Mars

NASA and the European Space Agency are studying a notional Mars Sample Return (MSR) campaign that would consist of a series of three missions with the overall goal of bringing samples of Martian rock and atmosphere to Earth. In a potential lean MSR architecture [3], the first step—collecting and cashing samples—would be completed by NASA's Mars 2020 rover. The notional MAV and a Sample Return Orbiter (including an Earth Return Vehicle) would be responsible for launching the samples into Mars orbit, transferring them to the Earth Return Vehicle and returning them to Earth. These latter two elements could launch as early as 2026. [4] In order to meet these timelines, technology development for the MAV has been ongoing.

A system study completed in 2014[5] identified the hybrid as the lowest GLOM option and highlighted a number of benefits. Mars presents a unique environment for a rocket launch. It has cold and variable temperatures, but the hybrid is predicted to be able to survive in the Martian environment with only passive insulation. To reach orbit around Mars, two burns are required. If solid rocket propulsion is to be utilized for the mission, two stages would be required. A hybrid rocket can be turned off and restarted. Therefore, a Single Stage to Orbit (SSTO) hybrid is possible. Finally, the performance (Isp) of a hybrid is higher than that of a solid. However, the hybrid option is at a much lower TRL than the solid rocket option.

3. Technology Development Goals

Technology development has been ongoing with current focus placed on maturing the propellant combination through testing at full scale. The motors being tested have a path towards flight configurations, but take advantage of ground weight materials and components for cost and increased safety factors. Materials are being evaluated for flight and the motor performance is being refined.

3.1 Propellant Combination

The propellant combination being proposed for a potential hybrid MAV is brand new. The first tests of the wax-based fuel, SP7, and MON-3 oxidizer were carried out in 2016. The first tests with the flight oxidizer, MON-30, will take place in late 2018/early 2019. Preliminary materials testing has been completed on the fuel. However, a more thorough evaluation will be completed this year. Information on MON-30 is available in the Air Force Handbook[6], but Handbook states 'additional characterization (or confirmation) of the N_2O_4-NO system is recommended', so addition MON-30 characterization is planned.

3.2 SP7 Development

The simple, centre perforated design enabled by liquefying fuels made a wax attractive for a hybrid MAV. However, standard paraffin wax is not very strong and could not operate up to the high temperatures originally being considered for MAV (~60 C). Note, that currently, the high temperature being considered is only 40 C. Paraffin-based hybrids typically have a fuel grain inner to outer diameter ratio of two, which limits the volumetric loading of the fuel.

SP7 is a wax based fuel that was developed by Space Propulsion Group, Inc., specifically for this application. The regression rate is about 60-70% that of neat paraffin. This decreases the thrust of the motor, making it easier to control during the coast after the first burn. The coefficient of thermal expansion (CTE) for SP7 is quite high. The grains shrink by approximately 20% during casting and are expected to move noticeably under Mars thermal cycling. Therefore, a fuel grain made up of multiple segments is being used to allow for differences in expansion with temperature.

The fuel grains are manufactured at Marshall Space Flight Center (MSFC). Liquid SP7 is poured into a container resembling a cake pan and cooled at a controlled rate in an oven. They are cast in multiple segments, machined to size and tolerance and assembled into full-scale fuel grains.[7] A full-scale fuel grain, made up of four segments is shown in Fig. 1.

Due to the cool down process, there are still questions on the stress state of the fuel after solidification of the liquid SP7. Earlier ambient cooled grains had grains that cracked frequently during cool down. Modelling of the cool down process will be done examine what the stress state in the grain and could lead to cooldown modifications.

Fig. 1. A multi-segment fuel grain (fourth segment not shown).

Subscale hotfire testing was carried out at MSFC to determine if multiple segments would affect the regression rate of the fuel. Both bonded and unbonded multi segment grains were tested. The unbonded segments displayed uniform regression. The bonded grains burned unevenly at the segment boundaries. The unbonded, multi-segment grain was selected for the full-scale testing.

4. Recent Progress

4.1 Full-Scale Hotfire Testing

Hot fire tests at approximately full scale (28 cm) were carried out at Space Propulsion Group, Inc. and Whittinghill Aerospace, LLC. Each vendor was tasked with determining their own design from a provided specification, aiming for high c* efficiency (>95%), stable combustion (indicated by <5% variation in peak-to-peak chamber pressure), multiple burns on the same fuel grain, a long duration burn and demonstration of LITVC.

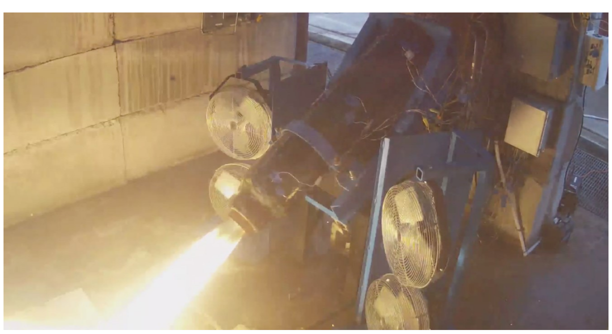

Fig. 2. Hotfire test at Space Propulsion Group.

Space Propulsion Group's design utilized a composite case (Figure 2). They tested multiple motors at their facility in Butte, MT. The fans shown in the image above were a safety precaution to prevent MON from getting trapped near the test stand in case of a non-ignition. SPG enjoyed minimal nozzle erosion for tests up to 32 seconds in duration.

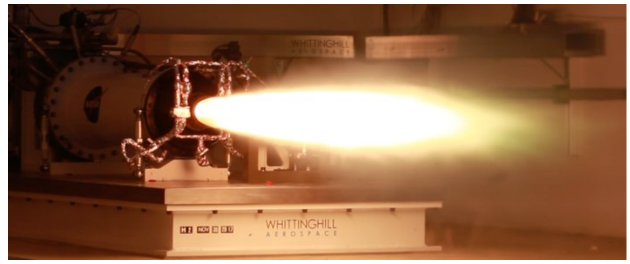

Fig. 3. Hotfire test at Whittinghill Aerospace.

Whittinghill Aerospace tested several configurations in a metal case at their test site in Mojave, CA. They completed an autonomous restart (85 s first burn and 5 s restart) as well as a near full duration burn (90 s). Excessive nozzle erosion was observed in these tests, but minimal erosion was found near the LITVC injection ports. The LITVC was injected a good distance from the throat, however, it is possible that the overall nozzle erosion masked some erosion at the LITVC ports.

Both vendors found that additional energy was required to vaporize the MON3 and achieve stable combustion with this propellant combination. Various methods of achieving this were attempted, the most successful of which was injecting a small amount of TEA/TEB into the motor for the duration of the burn. The minimum amount of heat addition for stability will be evaluated this year. It is expected that this will change as the testing moves from MON-3 to MON-30, since it is expected that the MON-30 requires less energy to vaporize.

4.2 LITVC

Liquid Injection Thrust Vector Control was demonstrated at both vendors. Whittinghill collected data on multiple tests with flight-like valves. SPG completed a single pulse with a ground weight valve to show feasibility. Neither design is representative of what would actually be used on Mars. The injectant for both cases was MON-3. Additionally, the injection point was designed for an Earth ground expansion cone. The actual Mars flight design area ratio will be about ten times higher (40) and therefore, the optimal injection location is not anticipated to be the same. However, data collected could help anchor a model to determine performance and propellant budget for a MAV.

A test of the LITVC system at Whittinghill Aerospace is shown in Fig. 4. The still image was captured during an LITVC event and a dark spot can be observed in the plume due to the injection of MON-3. It is visible directly adjacent to the left LITVC valve, near the exit of the nozzle. The feature is more clearly seen when compared to Fig. 3 from the same test. Whittinghill collected quantitative data during multiple actuations over two LITVC tests.

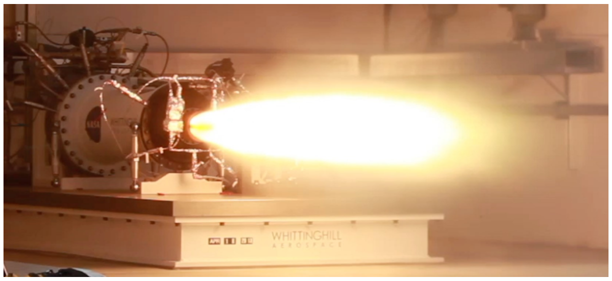

Fig. 4. LITVC actuated during a ground test of the Whittinghill motor (same test as Fig. 3).

4.3 Hypergolic Ignition

A hybrid rockets are often ignited with small pyrogens. This method could be at a disadvantage if the igniter requires thermal control in Mars ambient conditions. It would be much more elegant to ignite the motor with a hypergolic reaction between the oxidizer and the fuel like most storable bipropellant engines. However, one of the main advantages of the waxed based fuel is that it is inert and therefore is not hypergolic with the oxidizer. Even so, two methods of hypergolic ignition are currently being tested.

The first is using a liquid: TEA/TEB with the MON-30 oxidizer for ignition and to add additional heat at the front of the motor during combustion. TEA/TEB is often mixed with oxygen to ignite liquid engines. However, preliminary testing indicates that it is also hypergolic with MON. Testing of this combination to date has used a small amount of oxygen to initiate combustion of the SP7 in the full-scale hotfire test configuration before the MON is initiated. However, TEA/TEB ignition with only MON will be tested in the coming months.

The second option is to add hypergolic additives to the fuel grain. Prior to the need for the MAV, few solid materials that are hypergolic with MON's were published in literature. Drop testing at Penn State[8] and Purdue[9] identified candidate solid additives. Multiple, repeatable ignitions of SP7 with Sodium Amide and Potassium Bistrymethylsilyl Amide (PBTSA) have now been demonstrated at Purdue[10] (see Fig. 5) and several more attractive additives have been selected for future testing. Behaviour of these hypergolic additives under near vacuum conditions and with MON-25 or 30 will be determined this year.

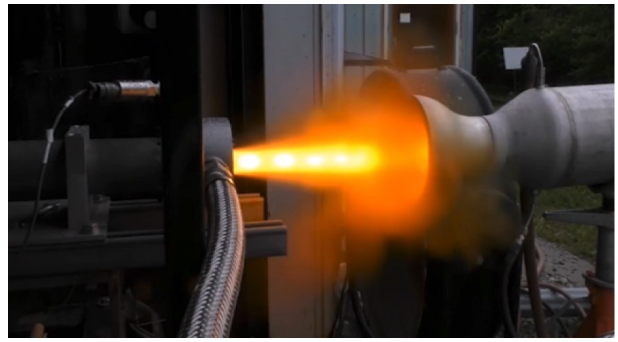
Fig. 5. Hypergolic Ignition of SP7/Sodium Amide with N_2O_4

Solid hypergolic additives are attractive for the reduction in system complexity that they enable. Since they are mixed directly with the fuel, no separate igniter is required. The additives can do more than just initiate combustion. They impart energy into the system, improving combustion stability with N_2O_4 and low MON concentrations (e.g. MON3). As described in the previous sections, the full-scale hotfire testing revealed the difficulty of vaporizing MON3. Current full-scale testing achieves this through the addition of a liquid hypergolic material. However, there is no reason that the same goal could not be achieved with these solid additives.

Solid hypergols introduce several challenges. The first is that adding these materials changes the material properties. It is well known that wax is a good sealant. If the material is placed into melted wax, the wax inhibits the additive from coming into contact with the oxidizer. Purdue has achieved success by mixing powdered wax and additives and compressing them into fuel grains. This way, the additive is not completely encapsulated by the wax. The density of the compression moulded grains is about 98% that of cast SP7. While this decreased density is not desirable, it is not a show stopper. The bigger problem may be that the material properties are expected to change as well. This will be determined shortly. Previous thermal cycling of SP7 with aluminium particles did not demonstrate substantially different behaviour from that of neat SP7. However, this test was completed with aluminium particles melted into the SP7, not compression moulded. Therefore, the thermal cycling will have to be repeated if solid additives are to be incorporated into the fuel grain.

The second challenge is in handling. Once hypergolic material is added to the previously inert fuel grain, it will require special handling. Most additives, such as Sodium Amide and PBTSA, react with moisture in the air. This decreases their reactivity with MON. Therefore, the fuel grain cannot be exposed to air. The motor will have to be sealed throughout integration and it could not be hydro tested.

5. Future Plans

The hybrid design will be matured and technology development will continue through summer 2019. The major focus of the development program is the shift to full-scale testing with MON-30 at the expected operating temperature, -20 C. Additionally, the behaviour of the proposed materials in the motor will be evaluated over the range of expected temperatures (-70 C to +40 C). The CTE of each material will be determined to ensure that the internal design of the motor is feasible over these conditions. Different adhesive methods and materials will be evaluated and the most promising candidates will be tested. A thermal cycled motor will be tested in Fall of 2019 under Mars-like pressure conditions.

The best method for planetary protection on a hybrid MAV is still an open question. The fuel will be tested to determine it potential to support bioburden. Assuming the wax is able to support microbial life, methods for sterilizing the fuel will be evaluated. Dry heat microbial reduction would be challenging, since the fuel begins to soften around 80 C and melts at around 100 C, both standard heat sterilization temperatures.

In parallel to the technology development, MAV vehicle level systems studies are underway and other options (such as a two-stage solid) are being evaluated. The non-propulsion system masses are being refined as well. This will be critical to determining if a hybrid MAV can meet the desired mass and volume constraints.

A potential avionics system and several IMUs are slated to fly with the Peregrine hybrid rocket motor in early Spring 2019. In addition to information about potential subsystem masses, this much higher thrust launch of a paraffin/N_2O hybrid could give some insight to the induced environments and the challenges they impose on a hybrid MAV. Finally, Sample Return Lander studies are being led by JPL and MAV accommodation by the lander will continue to be a major driver of the design.

6. Conclusions

A hybrid option is being studied for a potential Mars Ascent Vehicle. In order to make a potential 2026 launch opportunity, a closed MAV architecture, but not necessarily a final design, will be needed by the end of FY2019. The hybrid option for a potential MAV requires substantial engineering in order to be adopted for a potential MSR campaign. However, four years of technology development and maturation have not identified any “show stoppers.” Technology development is ongoing. The major focus of this year’s technology development program will be full-scale testing of the wax-based fuel and MON-30 oxidizer at the desired launch temperature (-20 C).

Acknowledgements

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